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Temporal information and children's and adults' causal inferences

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Three experiments examined whether children and adults would use temporal information as a cue to the causal structure of a three-variable system, and also whether their judgements about the effects of interventions on the system would be affected by the temporal properties of the event sequence. Participants were shown a system in which two events B and C occurred either simultaneously (synchronous condition) or in a temporal sequence (sequential condition) following an initial event A. The causal judgements of adults and 6–7-year-olds differed between the conditions, but this was not the case for 4-year-olds' judgements. However, unlike those of adults, 6–7-year-olds' intervention judgements were not affected by condition, and causal and intervention judgements were not reliably consistent in this age group. The findings support the claim that temporal information provides an important cue to causal structure, at least in older children. However, they raise important issues about the relationship between causal and intervention judgements.

Keywords: Causal reasoning; Interventions; Time.

Given the central role played by causal cognition in how we deal with the everyday world, it has long been considered important to describe and explain how children learn and reason about causal relationships (see e.g., Piaget, 1969; Shultz, 1982; Sperber, Premack, & Premack, 1995). A new wave of theorising, the causal Bayes nets approach (e.g., Gopnik et al., 2004; Gopnik, Sobel, Schulz, & Glymour, 2001; Sobel, Tenenbaum, & Gopnik, 2004), has brought this issue to the fore, leading to a reconsideration of the

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principles underlying children's causal inferences. This account captures causal learning in terms of the construction of models of the structure of the causal relationships between variables. Thus, one of the things that is distinctive about this approach is that it has made clear the necessity of exploring how children reason about the causal structure of the relationships between novel variables. For instance, when faced with a three-variable system ABC, how do young children learn that the causal structure is that of, for example, a common cause (A independently causes both B and C), causal chain (A causes B which causes C), or common effect model (both A and B independently cause C)?

In Gopnik et al.'s (2004) account, models of causal structure are assumed to represent patterns of conditional probabilities between variables, and research in this tradition has suggested that children are appropriately sensitive to such patterns (e.g., Gopnik et al., 2001; Sobel et al., 2004). The aim of the current study is not to examine such sensitivity; this has been explored in detail elsewhere (see Special Section of *Developmental Science*, 2007). Rather, we focus on the role of a specific type of information that has featured prominently in research on adults' learning of causal structure—temporal information. The ways in which adults' judgements of causation are informed or affected by temporal information have recently attracted much attention in the research literature (e.g., Buehner & May, 2002, 2003; Buehner & McGregor, 2006; Hagmayer & Waldmann, 2002; Lagnado & Sloman, 2004, 2006; Waldmann, 2001; White, 2006), with research findings providing interesting challenges for existing accounts of causal learning (Lagnado, Waldmann, Hagmayer, & Sloman, 2007). Indeed, in their review of this literature Lagnado et al. (2007) have argued that temporal information provides “a fundamental cue to causal structure” (p. 159), even to the extent that it can override other types of cues (Lagnado & Sloman, 2006). Despite this, little recent developmental research has addressed this issue, although the role of temporal information has featured prominently in earlier research on children's causal learning. Thus the primary aim of the current study is to examine whether children, like adults, will use temporal information as a cue to causal structure.

The second aim of the study is to examine the relationship between children's judgements regarding the causal structure of a system and their predictions about the effects of interventions on the system. Descriptions of causal learning in terms of the construction of models of a system's structure have led to a consideration of the relationship between causal judgements and judgements about what would happen if a variable in the system were intervened on. Indeed, it has been argued that even young children can use their causal representations flexibly to generate appropriate and novel interventions on a system (Gopnik et al., 2001; Schulz, Kushnir, & Gopnik, 2007b; Sobel et al., 2004). The empirical issue that we are interested in is

whether children's causal models of a system support not just judgements about how variables are causally related, but judgements about the effects of intervening on variables in the system (Hagmayer, Sloman, Lagnado, & Waldmann, 2007). For example, if children judge that the system they have observed is a causal chain ABC, will they also judge that C will not operate if B is disabled? Thus, in our studies children were asked to make not just judgements about causal structure but also judgements about the hypothetical effects of interventions on variables in the system.

EXTRACTING CAUSAL STRUCTURE

There have been a large number of studies that have addressed the role of temporal information in children's causal judgements (e.g., Bullock & Gelman, 1979; Mendelson & Shultz, 1976; Schlottmann, 1999; Shultz & Mendelson, 1975; Siegler & Liebert, 1974; Sophian & Huber, 1984). Although the findings provide a somewhat mixed picture of developmental patterns, safe conclusions that can be drawn from the literature are that by at least 4 to 5 years, if not earlier, children's judgements reliably obey the temporal priority principle (Bullock, Gelman, & Baillargeon 1982), and that even very young children's causal judgements are often strongly affected by temporal contiguity (see Schlottmann, 1999). Rather than simply examining the effects of temporal continuity or whether judgements respect the temporal priority principle, the current studies will focus on whether causal structure judgements are systematically influenced by the temporal order in which events have occurred. Studies with children beyond the infancy period have typically used paradigms in which there is a clearly identified effect (e.g., a jack-in-a-box jumping up). In contrast to studies of structure learning in adults, children have merely had to decide whether, for example, event A or event B caused this effect, rather than having to make more sophisticated judgements about the nature of the causal structure of a system. In Lagnado and Sloman's (2004, 2006) studies, the adults' task is usually to decide on the most appropriate causal model of the relationship between three or four variables, with there being a number of alternative models (e.g., common cause, casual chain, or common effect models) to choose from.

Some initial studies have been conducted to examine if young children can also learn to discriminate between different causal structures (see Gopnik et al., 2004). Most notably, Schulz, Gopnik, and Glymour (2007a) explored whether young children can use information about the effects of interventions on variables in a system to extract causal structure. The role of intervention information has been viewed as particularly important in recent accounts of causal learning, because information about the effects of intervening on (i.e., selectively fixing the value of) a variable can

discriminate between causal structures that are difficult to tell apart through observation of covariation alone (Hagmayer et al., 2007; Lagnado & Sloman, 2004; Schulz et al., 2007b; Steyvers, Tenenbaum, Wagenmakers, & Blum, 2003). To use a familiar example from the literature, it is difficult using observation alone to discriminate between a causal chain in which A causes C and C causes B and a situation in which C is a common cause of B and A, since covariation information is identical in both cases (see Lagnado & Sloman, 2004; Schulz et al., 2007b). However, if the value of C is selectively intervened on, it should be possible to easily discriminate these structures. For example, making C happen will increase the likelihood of observing B but not A if the structure is the causal chain, but will increase the likelihood of both A and B if the structure is the common cause one (see Sloman & Lagnado, 2005).

In Schulz et al.'s (2007a) study, a range of interventions on a novel three-variable system (a set of gears), was demonstrated to 4-year-old children, after which they were presented with different anthropomorphised diagrams depicting causal structure. Children appeared to be able to use intervention information to select the appropriate causal structure. Thus, Schulz et al.'s (2007a) study provides some preliminary evidence that young children may be able to extract causal structure when provided with one type of information: intervention information. However, their study was not designed to address the additional issue of whether temporal information may assist children in determining causal structure in a manner similar to that found in adults. Lagnado and Sloman (2004, 2006) have argued that in many scenarios the usefulness of intervention information may be to a large extent (though not fully) explained by the fact that interventions normally provide us with temporal order information. They point out that making an intervention is often accompanied by temporal order information: If you intervene to make B happen, and then C happens, not only are you provided with information about consequences of your intervention but you are confronted with a demonstration in which B has occurred temporally prior to C. That is, temporal cues are usually "built into the nature of an intervention" (Lagnado & Sloman, 2004, p. 869).

Lagnado and Sloman (2006) argued that studies on the effects of interventions need to disentangle the provision of information about the consequences of interventions with the provision of temporal order information. In their own study they achieved this by pitting temporal order information against intervention information. By this means Lagnado and Sloman have demonstrated that participants preferentially use information about the temporal order in which events have happened in order to decide on a causal structure, even when they have been made aware that such information may be misleading and even when it runs contrary to conditional probability information provided by carrying out interventions.

On the basis of these findings, they have suggested that adults frequently use a simple temporal cue heuristic along the lines of “if you perceive or produce an event, infer that any subsequent correlated changes are effects of that cause” (Lagnado & Sloman, 2004, p. 896). Applying this heuristic iteratively to each pair of events that one observes will affect causal structure judgements. So, for example, if a participant views an event sequence in which event A happens and then event B occurs, followed subsequently by event C, use of this heuristic will lead them to conclude that event A caused event B which then caused event C—a causal chain structure. In Lagnado and Sloman’s studies, participants appeared to rely heavily on temporal order information in this way.

THE CURRENT STUDY

The conclusion that can be drawn from Lagnado and Sloman’s (2004, 2006) studies is that temporal information may provide an important class of information about causal structure in and of itself, and as such is one that needs investigation in children. Our study addressed this issue. Lagnado and Sloman’s experiments have already clearly demonstrated that adults are likely to infer a causal chain structure when they observe event A followed by event B followed by event C. Furthermore, their findings suggest that if participants were to view a sequence in which event A happens and then events B and C happen simultaneously, they would be likely to judge that A is a common cause of B and C. Our study examined whether children’s judgements about causal structure are similarly affected by the timing of events. Our task differs from those of Lagnado and Sloman in that the use of temporal information was not pitted against intervention information (doing so involves introducing quite complex scenarios where the temporal order in which participants find out about the consequences of interventions differs from the order in which events actually unfold). Rather, the primary aim of the study was simply to explore whether children will exploit temporal information in a scenario in which they have been provided with minimal information on which to infer causal structure.

It is not known whether under such circumstances children’s causal judgements, which are derived from information other than that from performed or observed interventions, are commensurate with judgements about what would happen in hypothetical circumstances given certain interventions. In one of Schulz et al.’s studies (2007a, Exp. 2), preschool children were better than chance in making predictions about the effects of interventions on a causal system. So, for example, if the relationship between three variables A, B, and C was a causal chain, children were more likely than chance to predict that if B is intervened upon such that it can no longer operate, then C will no longer occur following the occurrence of A.

However, in that study children were actually explicitly told what the causal structure of the relationships was, rather than having to derive it themselves, whereas in our study children had to initially infer causal structure. Thus, the secondary aim of the study was to explore whether temporal information has a similar effect on judgements regarding interventions as on causal judgements, and whether there is indeed consistency between causal judgements and judgements about the consequences of interventions.

This issue is important because it has recently been argued that not only may intervention information play a useful role in deriving causal structure, but that the way causal relationships are represented should allow participants who have learned a causal structure to straightforwardly predict the effects of interventions on variables in the causal system (Hagmayer et al., 2007; Schulz et al., 2007b). In particular, researchers who describe causal representation in terms of models of causal structure have argued that such representations can be used to make simple inferences about the effects of real or hypothetical interventions (Hagmayer et al., 2007; Sloman & Lagnado, 2005; Waldmann & Hagmayer, 2005). If these suggestions are correct, then we might expect to see that judgements about the effects of interventions on a variable in a system are consistent with causal judgements about the relationships between the variables and are affected in the same way by temporal cues.

EXPERIMENT 1

In this experiment we devised a very simple scenario in which temporal information may provide a cue to causal structure. The scenario was as follows: an initial event A was subsequently followed by two events, B and C. The three events covaried with 100% reliability, such that each time A occurred, B and C followed. From the covariation information alone one may conclude that the three events are causally related, but no further conclusions can be drawn about the nature of these relationships. It was hypothesised, however, that the presence of temporal information may inform judgements of how the three events are causally connected, i.e., the underlying causal structure of the system. Specifically, it was predicted that when events B and C occur simultaneously after event A, a common cause structure will be inferred, whereas when events A, B, and C form a temporal sequence, a causal chain structure will be inferred (see Figure 1). Three age groups were tested: 4-year-olds, 6–7-year-olds, and adults. Based on previous research on children's use of temporal information in causal judgements, we predicted that the 6–7-year-olds were likely to use such information in a manner similar to that of adults. Findings from some existing studies might suggest that 4-year-olds are also likely to exploit such information.

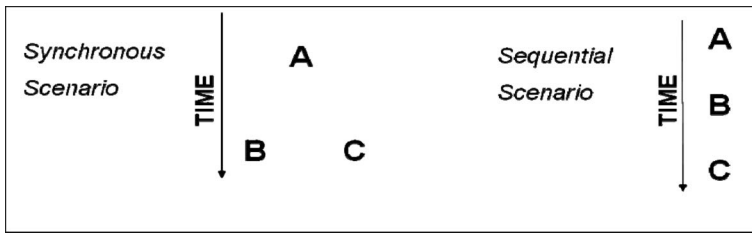


Figure 1. The two temporal conditions.

Method

Participants. Three age groups of participants took part in the study: 50 4-year-olds ($M=55$ months, $Range=48-63$ months), 58 6–7-year-olds ($M=84$ months, $Range=76-90$ months), and 60 adults ($M=25$ years, $Range=18-59$ years). There were 95 females and 73 males in total. Children were recruited from a number of schools and preschools, and testing took place individually in their schools. Adult participants were approached on the university campus and asked whether they would volunteer to take part in a short experiment. They were not paid for their participation.

Apparatus. A box was designed and constructed for the purposes of this experiment. The box was rectangular and measured 33 cm \times 45 cm \times 15 cm. The box housed three devices on its surface, the action of which constituted events A, B, and C. Device A was a red toggle that could be manually moved back and forth. The second device was a blue square plate, which rotated around a central axis at a frequency of 120 Hz. The third device was a black and white plunger that moved up and down on the vertical plane at a frequency of 60 Hz. The devices were approximately equal in size (the plunger and toggle were 5 cm in height while the plate was 5 cm across) and in their resting state they were clearly visible. The devices were positioned on the surface of the box to form an equilateral triangle. Event A (the movement of the toggle) was always manually instigated by the experimenter. The action of the other two devices was driven by hidden motors and their timing controlled by a laptop computer placed inside the box. This allowed for maximal control over the temporal characteristics of the experimental sequences.

Procedure. Participants were randomly assigned to one of two conditions: either the synchronous or the sequential condition. Figure 2 illustrates the temporal characteristics of a single demonstration trial in both conditions. The sequence of events in both conditions was initiated by the

experimenter pushing the toggle forward (event A). The timing of each demonstration began the moment the toggle was pushed. Aside from these differences in the timing of events, the procedure was identical across the two conditions.

At the start of the experiment participants were invited to have a look at the "special box" of the experimenter. All participants were seated facing the box adjacent to the positions of the plunger and plate (used in events B and C), while the experimenter sat on the opposite side of the box, behind the toggle (used in event A). In the initial orientation to the box, children were asked first to point out the three devices and then to identify the colour of each of them; the responses they provided were used by the experimenter as referents for the three devices throughout the rest of the experiment. Children who were unable to discriminate between the three devices on the basis of their colour were not included in the subsequent analysis. When testing adults the devices were labelled by the experimenter as the toggle, plate, and plunger. Children were then instructed as follows: "Now then, I want you to watch what happens when I move the red one [experimenter points to the toggle]. OK?" The experimenter then pushed the toggle forward to initiate the first demonstration. After the first demonstration the experimenter said to the child, "Did you see that? Let me show you again." Three further demonstration sequences followed. Children were then asked two direct, forced-choice causal questions about events B and C: "Can you tell me, which one of the other two makes the blue one [plate] go?" and "Which one of the other two makes the white one [plunger] go?" Adult participants were asked to observe the box while the experimenter pushed the toggle. They also observed the experimenter initiate four demonstrations after which they were asked the same two forced-choice causal questions about events B and C (with the adult referents for the devices used).

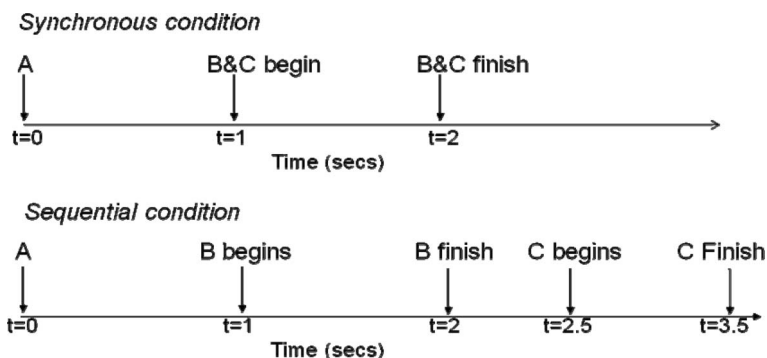


Figure 2. The temporal characteristics of each condition.

After answering the causal questions, children then observed two further demonstrations as a reminder of the event sequence, after which they were asked two intervention questions. After the demonstrations had finished, the experimenter intervened on the device used in either event B or C, manually holding it and thus preventing it from moving. It was then stressed to participants that the intervention completely disabled the action of the device. The experimenter said, "I am going to stop this one from going [intervention was then performed]. So now this one cannot go at all. It really cannot go." All participants were then asked a hypothetical question about what would now happen should event A occur. For example, when the plunger was disabled participants were asked, "If I push the blue one [toggle], will the red one [plate] still go?" After participants had given their answer the experimenter then disabled the other device (B or C) and asked a similar hypothetical question about the effect of this second intervention. Which specific device featured in event B and which in event C was counterbalanced across participants; likewise the order in which participants were asked about events B and C was counterbalanced for both the causal and intervention questions. However, the causal questions were always asked prior to the intervention questions.

Results

A small number of children in the 4-year-old group ($N=4$) were unable to name the colours of the three devices and were thus excluded from the experiment. Initial analyses revealed that the spatial locations of events B and C had no effect on responses to either the causal or intervention questions.

Causal questions. Responses to causal questions were categorised as follows. Responding that A caused both B and C was always coded as a common cause response, and responding that A caused B and B caused C was always coded as a causal chain response. Responding that A caused C and C caused B was coded as a causal chain response in the synchronous condition, but in the sequential condition this causal chain was inconsistent with the temporal order in which the events occurred because B had occurred before C. Thus, this type of response was coded as a time-inconsistent response in the sequential condition. (This response was not judged to be time-inconsistent in the synchronous condition because it remains possible that C could have caused B even though the two were perceived as occurring simultaneously, see e.g., the events used in Schulz et al.'s, 2007a, study.) Finally, judging that B caused C and C caused B was coded as a coupled response in the synchronous condition; in the sequential condition this response was again inconsistent with the temporal order of

events because C had occurred after B. Thus, this response was also coded as a time-inconsistent response in this condition.

Table 1 shows the percentage of participants in each condition whose responses were in each category. Responses categorised as coupled or time-inconsistent responses were infrequent among each of the age groups, with just eight of the 4-year-olds, two of the 6–7-year-olds, and none of the adults giving such responses. Chi-squared analyses examined whether the distribution of common cause and causal chain responses differed across the two conditions. (Note that responses categorised as coupled or time-inconsistent were excluded from these analyses because they were relatively infrequent and our predictions concerned the distribution of common cause and causal chain responses across conditions; omitting these responses from the analyses has the consequence that the *N* reported for each chi-squared analysis does not always match the total number of children tested in each age group.) The 4-year-old group showed no difference between the two conditions in the distribution of common cause and causal chain responses, $\chi^2(1, N = 38) = 0.11, p = .74$. However, it is important to note that although the distribution of the 4-year-olds' responses across conditions was not in line with a temporal cue hypothesis, this group did not entirely ignore temporal information. Crucially, very few children gave responses that suggested a belief in backward causation: only two children in the sequential condition judged that C was the cause of B, and in this condition a binomial test showed that the number of children who judged that A was the cause of B was significantly higher than the number who judged that C was the cause of B, $N = 23, p < .001$.

Turning to the older groups of participants, there was an effect of condition on the responses of 6–7-year-old group, $\chi^2(1, N = 56) = 7.08, p = .008$; in this group the majority of participants were categorised as giving the common cause response in the synchronous condition and the appropriate causal chain response in the sequential condition. Likewise

TABLE 1
Percentage of participants giving each response type to causal questions as a function of condition in Experiment 1

	4-year-olds		6–7-year-olds		Adults	
	<i>Synchronous</i>	<i>Sequential</i>	<i>Synchronous</i>	<i>Sequential</i>	<i>Synchronous</i>	<i>Sequential</i>
Common cause	39%	43%	62%	28%	80%	53%
Causal chain	35%	48%	31%	72%	20%	47%
Coupled	26%	–	7%	–	0%	–
Time-inconsistent	–	9%	–	0%	–	0%

– indicates that the response type does not apply in that condition.

the adult group also showed a significant effect of condition, $\chi^2(1, N=60)=4.80, p=.03$; again, most adults in the synchronous condition were categorised as giving the common cause response. In the sequential condition the adult pattern was somewhat different from that of 6–7-year-olds, and from that which we had predicted, in that responses were almost evenly divided between common cause and causal chain categories. Note, however, that a participant who believes the structure to be a causal chain in this condition (i.e., believes that A causes B and B causes C) is nevertheless justified in judging that A made both B and C happen, since the initial event A is represented as setting the chain in motion. Thus, some of the responses categorised as synchronous in this condition may nevertheless have been made by adults who extracted a causal chain structure (as the analyses of intervention responses below suggests).

Further analyses examined whether there were age differences in the extent to which participants' responses were affected by temporal cues in the predicted direction. For each age group we calculated the total numbers of responses across conditions predicted by a temporal cue hypothesis and the total number of responses unpredicted by such a hypothesis (collapsed across all other response categories), with common cause responses categorised as the predicted response in the synchronous condition and causal chain responses categorised as the predicted response in the sequential condition. The numbers of participants whose responses fell into the predicted categories varied significantly with age, $\chi^2(2, N=164)=6.68, p<.05$, with the 6–7-year-olds producing significantly more responses in the predicted categories than 4-year-olds, $\chi^2(1, N=104)=5.90, p<.02$, but not significantly more than adults, $\chi^2(1, N=118)=0.20, p>.05$. Thus there was an age effect in the extent to which temporal cues affected responding, in that older children and adults were significantly more likely to produce responses in line with a temporal cue hypothesis.

Intervention questions. As with the causal questions, the responses to the intervention questions were placed into categories that were analogous to the categories that responses to the causal questions were placed in (see Table 2). Answering yes to both questions (i.e., B will still go if C is prevented from operating and C will still go if B is prevented from operating) was categorised as a common cause response. Judging that B will still go if C is prevented from operating but that C will not go if B is prevented from operating was always categorised as a causal chain response. Judging that C will still go if B is prevented from operating but that B will not go if C is prevented from operating was also categorised as causal chain response in the synchronous condition but was classed as a time-inconsistent response in the sequential condition. Finally judging that neither C nor B will go if the other device is prevented from operating was classed as a

coupled response in the synchronous condition but a time-inconsistent response in the sequential condition.

Table 3 shows the percentage of participants in each condition who gave each response type combination. The majority of 4-year-olds in both conditions gave common cause type responses, and there was no difference in how responses were categorised across conditions. The 6–7-year-old group showed a mixed pattern of responding that also did not differ significantly between the conditions $\chi^2(1, N=45) = 1.14, p = .29$. Relatively few adults gave coupled responses in the adult group (six in total across both conditions); the majority of adults' responses were categorised as common cause in the synchronous condition and causal chain in the sequential condition. Chi-squared analyses showed that the distribution of common cause and causal chain responses in the adult group differed between conditions $\chi^2(1, N = 54) = 10.61, p = .001$. Of note is the fact that of the 16 adults in the sequential condition who had been categorised as giving common cause responses to the causal questions, the majority (10/16) gave responses to the intervention questions that were categorised as causal chain

TABLE 2
Response categories for intervention questions

	<i>A</i> <i>I*—C?</i>	<i>A</i> <i>B?—I*</i>
Common cause	Yes	Yes
Causal chain	No	Yes
Synchronous condition: Causal chain	Yes	No
Sequential condition: Time-inconsistent	Yes	No
Synchronous condition: Coupled	No	No
Sequential condition: Time-inconsistent	No	No

*Denotes an intervention on a variable that prevents it from operating.

TABLE 3
Percentage of participants giving each response type to intervention questions as a function of condition in Experiment 1

	<i>4-year-olds</i>		<i>6–7-year-olds</i>		<i>Adults</i>	
	<i>Synchronous</i>	<i>Sequential</i>	<i>Synchronous</i>	<i>Sequential</i>	<i>Synchronous</i>	<i>Sequential</i>
Common cause	61%	70%	48%	41%	60%	27%
Causal chain	13%	4%	28%	38%	23%	70%
Coupled	26%	—	24%	—	17%	—
Time-inconsistent	—	26%	—	21%	—	3%

— indicates that the response type does not apply in that condition.

responses. This suggests that in this condition most of those adult participants who judged that A caused both B and C when asked the causal questions nevertheless believed that the structure was that of a causal chain.

As with the analyses of responses to causal questions, further analyses examined whether there were age effects in the extent to which participants' responses to intervention questions were affected by temporal cues in the predicted direction. Responses to intervention questions were scored as predicted or unpredicted by a temporal cue hypothesis in the same manner as responses to causal questions (see above). The numbers of responses that fell into the categories predicted by a temporal cue hypothesis varied significantly with age, $\chi^2(2, N = 164) = 11.87, p < .01$. The 6–7-year-olds did not produce significantly more responses in the predicted categories than 4-year-olds, $\chi^2(1, N = 104) = 1.19, p > .05$, but did produce significantly fewer responses in the predicted categories than adults, $\chi^2(1, N = 118) = 5.70, p < .02$. Thus, there was an age effect in the extent to which temporal cues affected responses to intervention questions, with adults' responses to these questions being more likely to be as predicted by a temporal cue hypothesis than those of children.

Last, additional analyses examined the consistency of responses to causal questions and intervention questions in the two groups that showed an effect of temporal condition on answers to the causal questions. If it is allowed that judging A to have caused both B and C in the sequential condition is consistent with giving a causal chain response to intervention questions in this condition, 83% of adults gave consistent responses across both question types, but only 59% of the 6–7-year-olds showed such consistency. Chi-squared analysis showed that there was a significant difference between the groups in the number of participants who were consistent in their answers to the two question types, $\chi^2(1, N = 118) = 8.78, p = .003$.

Discussion

The responses of both the adults and the 6–7-year-olds to the causal questions support our initial hypothesis that temporal order information influences causal structure judgements. For both of these age groups there were differences in the pattern of responses to the causal questions across the two conditions in the predicted directions. The finding that timing influences causal structure judgements in these groups corroborates the findings of Lagnado and Sloman (2004, 2006). By contrast, the responses to the causal questions of the 4-year-olds did not differ across the two conditions. Moreover, for the intervention questions, the majority of 4-year-olds were categorised as giving a common cause response regardless of the temporal condition to which they were assigned. This may well reflect a yes bias in

response to the intervention questions, as common cause responses were defined as those in which yes responses were given to both intervention questions. The 6–7-year-old age group also did not reveal any difference in their response to the intervention questions across the two conditions despite having responded differently to the causal questions across the two conditions. In this group, however, responses categorised as common cause did not dominate the answers.

Interestingly, then, the three age groups each show a different overall pattern of response across the two question types. Four-year-olds showed no differential sensitivity to the temporal properties of events across the conditions in responses to either the causal or intervention questions. Adults, by contrast, showed a sensitivity to the temporal information manipulation in responses to both causal and intervention questions. Finally, while 6–7-year-olds' responses to the causal questions did differ between the two conditions, their responses to the intervention questions were not affected by the temporal properties of the demonstrations they had observed. Both adults and 6–7-year-olds were significantly less likely to give common cause responses in the sequential condition than in the synchronous condition, although in the sequential condition, the 6–7-year-olds gave more causal chain responses than the adults. However, the majority of adults in the sequential condition who gave common cause responses to the causal questions went on to give causal chain responses to the intervention questions. It may be the case that adults are more likely to give the cautious response that A is the cause of both B and C in the sequential condition, as this is correct regardless of the actual underlying causal structure.

Given that adults' responses to the intervention questions were typically commensurate with their responses to the causal questions in the way one would expect, it is somewhat surprising that 6–7-year-olds responses to the causal and intervention questions were not reliably consistent. This might suggest that when children have to make causal structure judgements without observing relevant intervention information (in this case, based purely on temporal information), they base their judgements on representations that do not support subsequent judgements regarding the effects of interventions.

EXPERIMENT 2

In our second experiment we re-examined the consistency of causal and intervention judgements in this age group but we changed the order in which children were asked each type of question. There were two reasons for this manipulation of question order. First, it may be the case that getting children to consider the hypothetical consequences of interventions leads them to generate representations of causal structure that support both

judgements about interventions and causal judgements. Second, and more prosaically, asking the questions in this order would also control for any explanation of children's performance on the intervention questions in terms of fatigue of having already answered two causal questions.

Method

Participants. A total of 60 6–7-year-old children ($M=86$ months, $Range=78$ – 92 months, 32 females and 28 males) took part in the study. They were recruited from local schools.

Procedure. The procedure was very similar to that of Experiment 1. After an initial introduction to the box, participants in both conditions passively observed four demonstration trials initiated by the experimenter. They were then asked the same two intervention questions as in Experiment 1 (question order counterbalanced). Children then observed two further demonstration trials as a reminder of the event sequence. Participants were then asked the same two causal questions as in Experiment 1.

Results and discussion

Responses to causal questions are shown in Table 4; the pattern for each condition closely resembles that found in Experiment 1. A chi-squared analysis examined whether the distribution of the number of answers categorised as causal chain and common cause responses differed across the two conditions. As in Experiment 1, relatively few children produced coupled or time-inconsistent responses and these responses were excluded from this analysis. The distribution of the number of answers categorised as causal chain and common cause responses differed significantly across the two conditions $\chi^2(1, N=55)=7.9, p<.01$. Responses to intervention questions were categorised in the same way as in Experiment 1. As in the previous experiment, the distribution of common cause and causal chain responses did not differ significantly between the two conditions, $\chi^2(1, N=37)=0.001, p=.97$. However, we note that in both conditions there were more responses categorised as coupled/time-inconsistent than in Experiment 1. Consistency of responses across causal and intervention questions was examined in the same manner as in Experiment 1; only 42% of children were consistent in their responses across the two question types.

Thus, the key findings of this experiment replicate those of Experiment 1, in that temporal information appears to inform causal judgements but not judgements regarding interventions in a 6–7-year-old group. The only difference of note in the response patterns found in this experiment and

Table 4
Percentage of children giving each response type as a function of condition in Experiment 2

		<i>Synchronous</i>	<i>Sequential</i>
Causal Questions	Common cause	57%	27%
	Causal chain	30%	70%
	Coupled	13%	—
	Time-inconsistent	—	3%
Intervention Questions	Common cause	43%	33%
	Causal chain	27%	20%
	Coupled	30%	—
	Time-inconsistent	—	47%

— indicates that the response type does not apply in that condition.

those found in Experiment 1 is that in Experiment 2 there were a larger number of children who responded “no” to both intervention questions. The majority of time-inconsistent responses in the sequential condition were of this form and by definition all of the coupled responses in the synchronous condition. It may be that children are more conservative in their responses to intervention questions if they have not yet been asked to make explicit causal judgements.

EXPERIMENT 3

In Experiments 1 and 2, in the 6–7-year-old group different patterns of performance were found on causal questions than on intervention questions. One possible explanation of this disparity is that although children of this age made judgements about the causal relationships between pairs of events in the predicted manner, in fact such judgements were made without extracting an overall causal structure that linked together the three events they had observed. In other words, children may have extracted something about the causal relationships between individual pairs of events but not reliably formed an integrated model of the relationships between all three events. For example, they may have judged that A caused B, and that B caused C, but not realised that the implication of this is that there is also a particular sort of causal relationship between A and C, namely a causal chain that runs from A to C through B. By contrast, it may be the case that adults found it easier to consolidate their judgements about connections between individual pairs of events into such an integrated model of overall causal structure. It is possible that only participants who possessed such an integrated representation were able to make intervention judgements about the system in a manner that was consistent with causal judgements. Indeed, the intervention questions themselves were cast in terms of the relationships

between all three events: Effectively, participants were asked to judge what would happen to C if A were to happen given that B could not happen.

In Experiments 1 and 2 we questioned children about which component had made another component operate, and inferred the causal structure they had extracted from answers to these questions. This mode of questioning (i.e., asking about the causal relationship between individual pairs of events) is similar to that used in some other studies of adult causal structure learning (e.g., Sobel & Kushnir, 2006). However, some studies with adults have used graphical representations of the relationships between variables, typically involving arrows depicting causal links (see Hagmayer et al., 2007). Previous research has indicated that even 4–5-year-old children are also able to understand simple causal diagrams that represent causal structure (Schulz et al., 2007a). Unlike direct causal questions about individual causal relations (such as those asked in Experiments 1 and 2), diagrams of causal models are potentially diagnostic of the presence of an overall integrated causal structure representation. The diagrams used in Schulz et al.'s (2007a) study differed from those used with adults primarily in the way causal relationships were depicted (components were anthropomorphised, with hands rather than arrows). In our third experiment we introduced similar simple pictures, which visually represented three different possible causal structures and asked both children and adults to select between them.

This design allowed us to distinguish between two possible descriptions of children's performance. First, it may be that children can report on causal relationships between pairs of variables, but have no integrated model of these relationships, and thus cannot make appropriate intervention judgements. If this is the case, we might expect children's choice of causal model to be inconsistent with answers to the causal questions. Alternatively, it may be that children of this age do in fact construct an integrated representation of the relationships between all three variables but they cannot use this to make intervention judgements, in which case their answers to causal questions would be consistent with their choice of causal model but still inconsistent with their answers to intervention questions. We predicted that an adult group's selection of causal model would be consistent with the responses they gave to the causal questions.

Method

Participants. A total of 60 6–7-year-old children ($M = 83$ months, $Range = 77–90$ months, 26 females and 32 males) recruited from local schools took part in the study. In addition, 52 adults completed the task ($M = 30$ years, $Range = 20–60$ years)

Materials. A new box was constructed for use in this study that was slightly larger than the previous box (35 cm \times 49 cm \times 17 cm). Three new

devices made up the three events: a blue ball set at an angle on a bent spindle that rotated in the horizontal plane on an elliptical path; a yellow square that rotated around its centre point in the horizontal plane; and a red bar that also rotated around its centre point in the horizontal plane. The three devices were interchangeable in each of the three ports associated with events A, B, and C, and which device was used in which port was varied between participants. The horizontal rotation of the components meant that the apparatus was more similar to that used in Schulz et al.'s (2007a) study, although the apparatus differed from theirs in that none of the components actually touched each other.

Three diagrams were used in the test phase. Schulz et al. (2007a) found that this was the maximum number that could be used with young children, and furthermore in Experiments 1 and 2 the overwhelming majority of children gave responses that were categorised as either common cause or causal chain responses to the causal questions, with relatively few categorised as coupled. The pictures consisted of a colour digital photograph of the box from above, with an image of a reaching extended hand representing the connections between the events (see Figure 3 for an example). In the common cause picture two hands emerged from the A component, with one directed at the B component and one directed at the C component. There were also two causal chain pictures. In the ABC picture a hand emerging from the A component reached towards the B component and a hand emerging from the B component reached towards the C

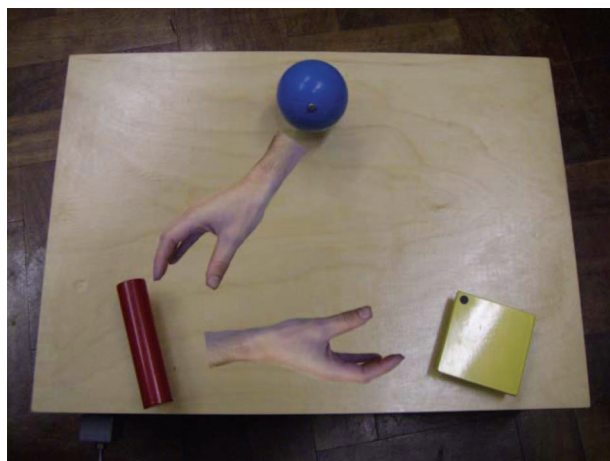


Figure 3. Sample diagram used in Experiment 3, showing a causal chain: the pictures of hands are overlaid on a photograph of the apparatus. The photographs presented to participants were in colour.

component; in the ACB picture a hand emerging from the A component reached towards the C component and a hand emerging from the C component reached towards the B component (in fact, which specific component featured in B and C events was counterbalanced across participants).

Procedure. The initial procedure was the same as in Experiment 1 up until the point at which the experimenter asked the causal questions. After these questions had been asked, the three pictures of the causal structures were then introduced. They were placed before participants in front of the box in a random order. Each picture was explained in the same manner. Both children and adults were told, for example, that "This hand shows that the [blue] one makes the [red] one go" and "This hand shows that the [blue] one makes the [yellow] one go." After each of the three pictures had been explained, all participants observed a further two demonstrations of the operation of the box that were initiated by the experimenter. Following this, participants were asked "Which picture do you think shows how the box really works?" If no picture was selected they were prompted with the question "Can you give me the picture which shows how the box really works?" After participants made their choice the other two pictures were removed, leaving their choice of causal structure diagram in full view in front of the box. Participants were then asked the same two intervention questions about a hypothetical scenario as in the previous experiments.

Results and discussion

Causal questions. Table 5 shows the percentage of both children and adults who gave each type of response to the causal questions. The pattern of response in both age groups is very similar to that found in the previous experiments, with a majority of those in the sequential condition giving responses that were categorised as causal chain responses, while those categorised as common cause responses were the most popular response in the synchronous condition. Again, relatively few participants made coupled or time-inconsistent responses, and these responses were not included in the subsequent chi-squared analyses of the responses to causal questions. The frequency of common cause and causal chain responses differed between the two conditions for the children's group, $\chi^2(1, N = 53) = 12.43$, $p < .001$. Likewise the frequency of common cause to causal chain responses also differed among the adult group in the manner predicted by the temporal hypothesis, $\chi^2(1, N = 51) = 12.48$, $p = .001$. As in Experiment 1, we examined the numbers of participants who produced responses predicted by a temporal cue hypothesis compared to the numbers who produced other

TABLE 5
Percentage of children and adults giving each response type as a function of condition in Experiment 3

		6-7-year-olds		Adults	
		<i>Synchronous</i>	<i>Sequential</i>	<i>Synchronous</i>	<i>Sequential</i>
Causal questions	Common cause	47%	11%	77%	31%
	Causal chain	37%	75%	19%	69%
	Coupled	16%	—	4%	—
	Time-inconsistent	—	14%	—	0%
Causal model choice	Common cause	67%	29%	73%	23%
	Causal chain	33%	71%	27%	77%
Intervention questions	Common cause	67%	64%	50%	23%
	Causal chain	13%	22%	23%	77%
	Coupled	20%	—	27%	—
	Time-inconsistent	—	14%	—	0%

— indicates that the response type does not apply in that condition.

types of responses, summed across conditions. There was no significant difference between the 6-7-year-old group and the adult groups in the number of participants who produced the predicted response pattern, $\chi^2(1, N = 112) = 0.85$, $p > .05$, a finding that is consistent with that of Experiment 1.

Causal model choice. Table 5 also shows the percentage of participants who selected each type of causal model in the two conditions. Note that no participants made time-inconsistent model choices in the sequential condition. There was a significant difference in the distribution of common cause versus causal chain model choices between the two conditions for the 6-7-year-olds, $\chi^2(1, N = 60) = 13.30$, $p < .001$, and also for the adults, $\chi^2(1, N = 52) = 13.02$, $p = .001$. The pattern of responses for both age groups was similar to that seen in response to the causal questions. However, among the children, the difference between the two conditions was somewhat more marked for the causal model choice. This is because more children chose the common cause model in the synchronous condition than gave answers to the causal questions that were categorised in this way. The numbers of participants who chose a model consistent with a temporal cue hypothesis did not differ significantly between the two groups, $\chi^2(1, N = 112) = .04$, $p > .05$.

Intervention questions. Children and adult's responses to the intervention questions are also given in Table 5. In this experiment the majority of children in both conditions gave responses that were categorised as common

cause responses to the intervention questions. As in Experiments 1 and 2 there was no significant difference in the distribution of common cause and causal chain responses between the two conditions, $\chi^2(1, N=50)=1.36$, $p>.05$. However, the distribution of common cause to causal chain responses among the adult group was significantly different across the two conditions, $\chi^2(1, N=45)=9.25$, $p=.001$. We also examined the numbers of participants who produced responses to the intervention questions that were consistent with a temporal cue hypothesis, collapsed across conditions. Although a higher percentage of adults produced the predicted pattern of responses (63% adults compared to 47% of children), the difference between the age groups just failed to reach significance, $\chi^2(1, N=112)=3.17$, $p=.075$.

Response consistency. Further analyses examined the consistency of both children's and adult's responses to causal questions, causal model selections, and intervention questions. A minority of children (40%) were consistent in their responses to causal questions and intervention questions, and only 47% produced responses to the intervention questions that were consistent with their causal model selection. Thus, as in previous experiments, intervention judgements were not reliably consistent with causal judgements. There was moderate consistency between causal model choices and answers to causal questions, with 67% of children choosing a causal model that matched their answers to causal questions. Note that consistency here may have been reduced by the fact that children had to choose between only three possible models—there was no model that matched the coupled response given by children to causal questions who had judged that B makes C go and C makes B go, so by default these children could not choose a consistent model. If children who gave such answers to the causal questions are excluded, 75% of children are categorised as choosing a causal model consistent with their answers to causal questions.

Adults, by contrast, revealed a high degree of consistency between their causal question responses and causal model choice (85%), between both their causal question responses and intervention question responses (80%), and between their causal model choice and intervention question responses (88%). Indeed 80% of the adult group was consistent across all three of the question types.

The results are broadly similar to the results from the first two experiments, with the use of the modified apparatus not appearing to have an effect on the overall pattern of response to the causal questions. The different patterns of causal model choice evidenced across the two conditions for both children and adults provide further support to the hypothesis that temporal order information guides causal structure judgements. The high rate of consistency between adults' responses to the

causal questions and their choice of causal model suggests that the causal models were interpreted as representing the causal structure of the apparatus as indexed initially by their response to the causal questions.

Overall there was no difference in the distribution of responses to the intervention questions between the two conditions for the children, and as a group they again failed to be consistent in their responses to causal questions and those to intervention question. This was despite the fact that children had the extra visual aid in the form of a causal diagram of their causal structure choice placed before them. Children's causal model choices were usually (although not always) consistent with the answers they had given to the causal questions, suggesting that most of them had indeed extracted a causal structure of the relationship between all three events. However, despite possessing such a representation, children's patterns of answers to intervention questions was quite different from that seen in their answers to causal questions, indicating that whatever the nature of this representation it did not appropriately support intervention judgements. This finding is at variance with adults' responses to the intervention questions, which were usually consistent with their causal structure inferences. This finding also runs contrary to those of Schulz et al. (2007a). However, we note that although Schulz et al.'s (2007a) findings provide some support for the claim that even younger children (4-year-olds) can use their representations of causal structure to make accurate predictions about interventions, the data from their experiment are somewhat limited. Inspection of the data (Schulz et al., 2007a, Exp. 2) indicates that although children made the appropriate predictions regarding the effects of intervention more often than would be expected by chance, in no case did the majority of their (relatively small) sample of children give the correct response (i.e., no more than 8/16 children gave the correct response on any trial type).

GENERAL DISCUSSION

The findings of this study strongly support Lagnado and Sloman's (2004, 2006) claim that temporal information is used as a cue to causal structure. In our task participants were given minimal information on which to base judgements of causal structure: They were not shown information about the consequences of interventions or covariation information that could be used to determine causal structure. Under such circumstances, 6–7-year-olds and adults recruited the temporal properties of the event sequence in making causal judgements. When two events B and C occurred simultaneously after an initiating event A, these age groups gave a pattern of responses that suggested they represented the causal structure of events as a common cause

structure. However, when event A was followed by B and after a short delay event C followed event B, these age groups gave a pattern of responses that suggested they represented the causal structure of events as a causal chain. The pattern of performance was consistent across all three experiments, suggesting that the effects of temporal cues on causal structure learning are robust.

These findings add to the growing body of research on adults' and children's causal structure learning. Other researchers have argued that both children and adults may be able to recruit conditional probability information and information derived from observing or performing interventions on a causal system in making causal structure judgements (e.g., Gopnik et al., 2004; Steyvers et al., 2003). Our findings complement this research by showing that, in the absence of such information, participants can use simple temporal cues to guide their causal structure judgements. We note that in previous studies examining causal structure learning, levels of accuracy in adult participants have sometimes been as low as around 20–30%, even when simple three-variable systems have been used (Lagnado & Sloman, 2004; Steyvers et al., 2003; note that a key difference between the events in these studies and those used in our studies is that causal relationships were probabilistic). Although it makes less sense to talk about levels of accuracy in our task, it is notable that the proportions of 6–7-year-olds and adults who performed according to predictions were relatively high (e.g., in Experiment 3 around 70% of participants in both age groups chose the predicted causal model diagram). In other words, although participants in other studies may sometimes have found it difficult to recruit covariation or conditional probability information, the majority of our participants readily made use of the temporal cues provided to them. Put together with other findings in the literature, an obvious conclusion is that a number of different cues can be recruited in causal structure learning. The implication of this is that models of the processes underpinning such learning need to account for how such cues are used and moreover how they are combined or weighted (see Lagnado et al., 2007, for a detailed discussion of this point).

Performance of 4-year-olds

Although the causal judgements of 6–7-year-olds and adults were informed by temporal information in the predicted manner, this was not the case for youngest group in the study, 4-year-olds (Experiment 1). There is general agreement that the causal judgements of children of this age are strongly affected by temporal contiguity (e.g., Mendelson & Shultz, 1976; Schlottmann, 1999), and studies with much younger children, using displays similar to those used in studies of adult perceptual causation, suggest that their

perception of events is, like that of adults, strongly affected by the temporal dynamics of the events (Cohen & Oakes, 1993; Leslie & Keeble, 1987; Oakes & Cohen, 1990). It may be that patterns of performance found in older children and adults reflect the employment of the sort of temporal heuristic that Lagnado and Sloman (2004, 2006) describe, and that such a heuristic is reliably adopted only with development, perhaps as a result of experience with a variety of causal systems. Or it may be that such heuristics are intact early in development, but that their effective use requires actually remembering the temporal properties of the events that have been observed, and that 4-year-olds have difficulty with remembering these features of the event sequence. It is possible that, with additional pre-training on the possible causal structures that may obtain between the test events, 4-year-olds would be more likely to consider temporal information in making their causal structure judgements. In Experiment 1 the experimenter did not explicitly cue children to consider specific possible structures (e.g., common cause or causal chain), but rather children were simply shown the events and asked to make judgements. It may be that younger children would make use of the temporal information in the context of a more structured and supportive task. In any case, our findings suggest that although temporal information may provide a basic and important cue to causation, it may not always play this role in the same way in young children as it does in older children.

This finding is potentially consistent with some other recent research that has shown that 4-year-olds have difficulty taking temporal information into account when making inferences (McColgan & McCormack, 2008; McCormack & Hoerl, 2005, 2007). Nevertheless, it is important to remember that it was not the case that 4-year-olds' causal judgements were logically inconsistent with the temporal properties of the events that they had observed. The temporal information that participants were provided with gave one cue to causal structure, but the events were in fact always consistent with a number of different causal structures. For example, in the sequential condition although there was a delay between the occurrence of event B and the occurrence of event C, it is perfectly possible that A was a common cause of B and C and that B played no causal role in the occurrence of C. The temporal properties of the event sequence in this condition only rule out any structure in which C is a cause of B. Indeed, only 2 out of 23 of the 4-year-olds made causal judgements that were categorised as indicating such a time-inconsistent representation of causal structure. This finding indicates that although 4-year-olds do not seem to use temporal information as a cue to structure in the same way as older children, nevertheless at the very least their judgements respect the temporal priority principle (i.e., that causes do not precede their effects), in line with Bullock and Gelman's (1979) original findings.

Judgements about interventions

In Experiments 1 and 3, adults' judgements about the effects of simple interventions on the system differed across the temporal conditions as predicted, and moreover their intervention judgements tended to be consistent with their causal judgements (consistency was around 80% in Experiment 3). However, 6–7-year-olds' judgements regarding interventions were not affected by temporal information in a similar manner to their causal judgements, and were not reliably consistent with their causal judgements even when a pictorial representation was present as a reminder of their causal structure judgement (Experiment 3). This might seem, at least at first sight, to be broadly inconsistent with recent suggestions that the types of representations that are used to make causal judgements can also be used to make judgements about the hypothetical or counterfactual effects of interventions on the system. (Hagmayer et al., 2007; Schulz et al., 2007b). Causal models theory accounts for such prediction making by assuming that the intervention fixes the value of the intervened-upon variable and then the remaining links in the model can be used to infer the consequences of the intervention (for greater detail, see Hagmayer et al., 2007). Certainly, the judgements of adults in our studies would suggest that they find such inferences relatively straightforward for the simple systems used in our studies (and see Waldmann & Hagmayer, 2005, for demonstrations that adults can reason about the consequences of interventions on more complex systems).

The issue of the relationship between causal judgements and judgements about the effects of interventions has become particularly important not only in the light of causal models theory, but also given a recent approach to causal cognition known as interventionism (Woodward, 2007, *in press*; see also various discussions in Gopnik & Schulz, 2007). This approach, which has its origins in a highly influential philosophical account of the nature of causation itself (Woodward, 2003), has only recently been considered as a psychological account of the nature of causal cognition. For present purposes we will define interventionism loosely as an approach that characterises causal knowledge as being, at its core, knowledge about the effects of observed, hypothetical, or counterfactual interventions. It can be contrasted with more traditional psychological accounts that characterise causal knowledge in terms of knowledge about mechanism (e.g., Shultz, 1982; White, 1995). Woodward contrasts these two types of approaches using the distinction between difference-making and causal process accounts of causation. Difference-making accounts, of which interventionism is a recent influential example, focus on the idea that causes make a difference to their effects, whereas causal process accounts focus on the processes by which causes result in their effects.

Traditionally, developmental psychologists have tended to appeal to causal process accounts in characterising the acquisition of causal knowledge. For example, Shultz (1982) described causal learning as involving a grasp of the principles of generative transmission, with causal learning in essence involving learning about the mechanisms by which such transmission occurs. Schulz et al. (2007b) argue that while it may be true that children may possess knowledge about the operation of specific mechanisms that they have encountered, such mechanism knowledge is not basic to representations of causal relationships. They point out that frequently even adults have little or no understanding of many of the mechanisms underpinning causal relationships in systems with which they are very familiar. Instead, what is argued to be basic to their causal knowledge is a sensitivity to the effects of intervening on or acting upon variables in such causal systems. As Schulz et al. (2007b) put it "A causal relation then is defined not in terms of its physical instantiation but in terms of the real and counterfactual interventions it supports" (p. 69). Thus it can be seen that, on this account, part of what it is to represent B as the cause of C in our task is a sensitivity to the fact that, all other things being equal, if B cannot occur (as is the case when it is intervened upon in the task), C will not happen. Given the interventionist account it is striking, then, that our 6–7-year-old group did not reliably make judgements about the effects of such interventions in line with their causal judgements and that their intervention judgements, unlike their causal judgements, were not affected by temporal information.

Do our results challenge the interventionist account? In making their judgements about the effects of interventions, children had to imagine a hypothetical scenario that they had not yet encountered (A operating while B or C were disabled), and the intervention in question was one that was carried out by the experimenter rather than the child him- or herself. In contrast to our findings, other recent research has suggested that even younger children can craft appropriate interventions if asked to act themselves to either prevent an event occurring or make it occur (see Schulz et al., 2007b, for review). It may be that it is making explicit verbal judgements about the hypothetical effects of another's interventions that children have difficulty with. Indeed, in his recent discussion of the relationship between children's causal judgements and judgements about the effects of hypothetical and counterfactual interventions, Woodward (in press) has argued that it may be possible to be " 'implicitly' guided by or sensitive to action-oriented counterfactuals even if one is not able to provide correct verbal answers to explicit questions about them". Another possibility is that the type of explicit judgement about interventions that children were asked to make was particularly difficult, and intrinsically more difficult than causal judgements. Whereas causal questions simply required

children to judge which component made another operate, the intervention questions were conditional in form (i.e., required “if ... then ...” judgements), and moreover were conditioned on two events: the disabling of B or C and the operating of A.

These considerations suggest that it might be possible to simplify the sorts of intervention judgements that children are required to make, either by asking children to make action-based responses or by asking intervention questions that condition only on a single event (e.g., by asking whether C would operate if B were manipulated). We have begun exploring these possibilities in our empirical work, with findings so far suggesting that even using such response modes, children find intervention judgements difficult in this task. Clearly, additional research is necessary on the relationship between causal judgements and judgements about the effects of interventions. Moreover, if interventionism is to replace the mechanism-based accounts that have been prevalent within the developmental literature, it is important to consider the extent to which such an account predicts a reliable consistency between such judgements.

We finish by considering a different perspective on why children’s causal judgements may have differed from their intervention judgements, which requires a consideration of the types of processes that are involved in the recruitment of temporal information in our task. One interesting possibility is that the cross-condition differences observed in causal judgements reflect the operation of processes more akin to those usually examined in studies of so-called perceptual causation, rather than reflecting the operation of an inferential reasoning process. Studies of perceptual causation have demonstrated that small differences in the spatio-temporal dynamics of an event sequence can affect whether or not two events are perceived as causally related (e.g., Michotte, 1963; Schlottmann, 2000; Scholl & Tremoulet, 2000). In our task the delays between events and the difference between temporal conditions were in the order of 0.5–1 second (following Lagnado & Sloman, 2004, 2006). Although these delays, and the event displays themselves, are quite different from those used in studies of perceptual causation, it may nevertheless be the case that participants tend to “perceive” that one event causes another, rather than making such judgements through reflecting upon the properties of the event sequences they have been shown (see, e.g., Schlottmann, 1999). In contrast, the intervention judgements undoubtedly require reflective reasoning. Judgements based on perceived causality are known to be affected by quite different types of task parameters than those based on more inferential processes (Schlottmann & Shanks, 1992), and it has recently been argued that they involve quite different brain structures (Roser, Fugelsang, Dunbar, Corballis, & Gazzaniga, 2005). It is possible that causal judgements that arise from more perceptually based processes might not easily support intervention judgements, and it may be the case

that it is only with development that they do. Indeed, Schlottmann's (1999) own research suggests that the relationship between judgements based on perceptual causation and more inferentially based judgements changes developmentally. We recognise that the distinction between causal judgements based on perception and those based on inference is not necessarily a clear-cut one (Schlottmann, 2000). Nevertheless, the issue of whether or not the effects of timing on causal judgements that we (and Lagnado & Sloman, 2006) have observed should be considered alongside findings from the perceptual causation literature is an intriguing issue and one that requires further investigation.

In conclusion, we have found strong evidence that both adults and 6–7-year-olds use temporal information to inform their judgements of causal structure in a situation in which there were minimal cues to causation. Our results and those of Lagnado and Sloman (2004, 2006) provide good reason to believe that temporal information in and of itself may provide an important cue to causal structure. However, 4-year-olds did not appear to use temporal cues in the same way as older children and adults. Adults' judgements of the effects of an intervention were similarly affected by the temporal properties of the event sequence that they had viewed, but this was not the case for children. This latter result is particularly striking in the light of recent interventionist accounts of causal cognition, since it suggests that children's representations of causal structure may not always support accurate judgements about the hypothetical effects of interventions. It may be the case that whether or not a tight relationship is found between children's causal and intervention judgements will depend on the information on which causal judgements are based, or the nature of the intervention judgements.

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